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Trophic State and Oxygen Conditions of Waters Aerated with Pulverising Aerator: The Results from Seven Lakes in Poland

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Abstract: Eutrophic lakes of all types are marked by oxygen shortage in the bottom waters during the summer season, which results in excessive release of phosphorus load. Therefore, numerous restoration activities (chemical precipitation, aeration) are being taken based on bottom-up control, which consists of limiting the nutrient pool available to lower trophic levels. The present study provides an efficiency analysis of pulverising aeration of waters in two stratified and five unstratified lakes located in Poland. The assessment was based on monitoring data (dissolved oxygen concentration (DO), % oxygen saturation (DO%), visibility of the Secchi disc (ZSD), the concentrations of: chlorophyll *a* (CHL), total phosphorus (TP) and total nitrogen (TN)) obtained before and after installation of the aerator on the lakes. The study was conducted during the spring and the summer seasons. Throughout the study period, the stratified lakes exhibited oxygen saturation <0.1%. Having completed the restoration activities, TN:TP ratio was found to gradually increase in all analysed lakes, which indicates that aeration may decrease phosphate content in the water column. In three lakes, the ratio was >17, so phosphorus became the most growth-limiting nutrient. The restoration activities on four unstratified lakes had no significant effect on the changes of the Carlson trophic state indices (TSI). Either individual values of the TSI(TP), TSI(CHL) and TSI(ZSD) were comparable, or the value of TSI(TP) was higher than one or both of the remaining indices for all of the lakes.

Keywords: pulverising aeration; oxygen conditions; trophic state; lakes

1. Introduction

Intensification of agricultural production and global population growth has resulted in the enhanced fertility of aquatic ecosystems. The primary and most efficient method for reducing the eutrophication rate of water reservoirs is to limit or eliminate the sources of biogenic supply to lakes. In the case of highly eutrophic reservoirs, such protective actions prove to be insufficient due to the so-called "internal loading" of reservoirs when biogenic compounds accumulated over the years in the bottom sediments are introduced into the water [1–4]. Therefore, numerous restoration activities are being taken based on bottom-up control, which consists of limiting the nutrient pool—particularly phosphorus compounds—available at the lower trophic levels. The primary process of reducing phosphate ions in water is shifting the processes of phosphorus circulation at the water/sediment phase boundary to its deposition in the solid phase.

Various methods for locking phosphorus compounds in bottom sediments, as well as limiting their solubility in water, have been developed. An example of the former method is the chemical precipitation of bioavailable forms of phosphorus with the compounds of calcium [5,6], aluminium [7–9] or iron [10–12], and the adsorption of such compounds using various kinds of sorbents, e.g., lanthanum-modified bentonite [13]. The latter group of methods comprise artificial aeration of lakes for the purpose of increasing the redox potential at the water/sediment phase boundary which, in turn, limits the release of phosphorus compounds from the bottom sediments. Artificial aeration is carried out by means of two methods: thermal destratification or hypolimnetic oxygenation while maintaining thermal stratification. The first method consists of aeration of the waters of the entire lake and is most commonly adopted during the summer stagnation period in small and deep lakes [14–16]. In aeration methods involving thermal destratification, compressed air is introduced to the waters above the bottom, at the deepest point of the lake, which results in induced rise of the water to the surface and, consequently, mixing of the water mass [15,17,18]. The hypolimnetic oxygenation method is used in deep lakes with thermal stratification [16,19–22]. It can be carried out using pneumatic aerators by means of injecting air or pure oxygen into hypolimnion water in a confined space and returning the oxygen-rich water to the lower layer of the lake. There are methods allowing oxygenation of the waters of shallow lakes, e.g., using the technique known as side stream supersaturation [23,24]. Another method is spraying water into air with the use of pulverising aerators. Pulverising aerators have high specific capacity, and the construction allows the use of renewable energy sources. In Poland, the most popular solution is the use of wind-driven pulverising aerators. These are distinguished by a simple design, insensitivity to changes in wind direction, and high resistance to water pollution. This technology can be used in deep lakes for the purpose of hypolimnion oxygenation, as well as in shallow lakes to eliminate the deoxygenated layer of the bottom waters (the so-called oxycline) occurring in the summer period [25,26].

The aim of this study is the assessment of the effectiveness of pulverising aeration of the waters of lakes located in West Pomeranian Voivodeship. The assessment was based on monitoring data obtained before and after deployment of the aerator. Long-term effects of the use of aerators were identified by means of analysis of the changes in oxygen conditions and the trophic state of the analysed lakes during the growing season.

2. Materials and Methods

2.1. The Study Lakes

The study objects were seven lakes located in Poland, in West Pomeranian Voivodeship (Table 1). The research included two dimictic lakes with thermal stratification—Barlineckie and Zamkowe—and five unstratified lakes—Nowogardzkie, Resko Górne, Głębokie, Starzyc, Trzęsiecko. In the period 2000–2014, a wind-driven pulverising aerator was installed in each of the analysed lakes (Table 2). The aerators deployed in polymictic lakes were additionally fitted with a coagulant dose-control system. The coagulant, i.e., PIX type (main ingredient—$Fe_2(SO_4)_3$), was applied in the growing season after installation of the aerator. The amount of the coagulant applied to pumped water was approximately 20 kg month^{-1}. In the following years, minimum coagulant doses of 5–15 kg ha^{-1} year^{-1} were used.

Table 1. Basic morphometric parameters of the analysed lakes.

Lake Name	Surface Area (10^3 m^2)	Average Depth (m)	Maximal Depth (m)	Volume (10^3 m^3)	Coastline of Lake (m)
Barlineckie	2591	7.2	18.0	18,579.8	10,450
Zamkowe	1328	12.9	36.5	17,100.0	10,950
Resko Górne	507	5.0	2.7	1358.4	7200
Starzyc	592	2.7	6.1	1580.0	5175
Trzęsiecko	2951	5.4	11.8	16,067.3	15,900
Głębokie	313	2.4	6.0	751.0	3950
Nowogardzkie	983	5.2	10.9	5087.3	5700

Table 2. The year of the aerator installation and mean values of dissolved oxygen saturation, TN:TP ratio for the analysed lakes in the spring and the summer season during the study years (superscript * means that only one measurement was done per season in this year).

Lake	Year of Study	DO%				TN:TP [mg mg^{-1}]		CHL [mg m^{-3}]	
		Surface Water		Bottom Water		Surface Water		Surface Water	
		Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Barlineckie	1994 *	106.0	95.0	102.7	<0.1	15.7	8.9	12.0	7.0
	2000	Aerator Installation							
	2001 *	124.0	114.0	64.0	<0.1	18.5	15.8	12.7	1.1
	2010	108.0	118.0	11.0	<0.1	20.8	26.8	4.0	4.6
	2016	112.0	136.0	90.0	<0.1	22.6	31.0	9.8	4.4
Zamkowe	1995 *	94.9	101.4	93.4	4.8	2.7	3.1	5.3	2.3
	2002	Aerator Installation							
	2010	73.0	101.0	49.0	1.0	3.7	12.4	24.2	72.6
	2015 *	94.1	88.5	<0.1	<0.1	7.8	10.4	56.2	15.0
Resko Górne	1994 *	91.4	104.0	72.5	53.3	17.1	4.6	4.5	74.3
	2003	Aerator Installation							
	2010	117.0	50.0	117.0	0.9	17.0	8.8	22.6	31.4
	2015 *	48.1	103.0	44.2	103.0	13.2	14.2	9.3	65.6
Starzyc	1997 *	139.0	126.0	152.2	101.0	15.6	7.5	42.2	58.9
	2003	Aerator Installation							
	2010	114.0	118.0	44.0	71.0	15.3	14.8	26.8	42.1
	2016	98.7	135.0	97.9	118.0	22.1	10.4	21.4	74.7
Trzęsiecko	2000 *	105.0	82.2	99.4	1.0	36.2	14.1	15.2	17.0
	2004	Aerator Installation							
	2008	95.9	101.0	90.2	0.6	33.9	33.5	9.7	11.7
	2010	98.0	132.0	67.0	1.0	31.7	21.5	30.9	23.3
	2011	150.0	111.0	71.0	3.0	79.4	25.0	20.8	13.4
	2016	118.0	70.1	6.4	13.6	31.6	8.5	9.4	32.3
Głębokie	2001 *	125.0	89.2	134.2	111.0	17.2	4.5	42.4	9.7
	2008	Aerator Installation							
	2010	107.0	129.0	77.6	<0.1	20.6	27.5	9.8	6.4
Nowogardzkie	1997 *	109.0	42.1	108.1	43.1	6.1	3.0	16.0	19.1
	2005 *	160.0	151.0	61.6	<0.1	8.9	5.2	37.2	57.5
	2009	151.0	87.0	79.0	1.0	5.4	2.7	9.8	6.4
	2014	Aerator Installation							
	2015 *	86.6	80.5	1.0	<0.1	25.0	5.5	12.2	20.3

2.2. *Aeration of the Lakes*

Pulverising aerators operate by taking up the bottom waters of a reservoir and dispersing it in the pulverising sector of the aerator, located on the surface of a lake, which is followed by the return of the water to the layer of the lake from which it was collected. The bottom water is taken up to the pulverising sector through hoses due to the rotation of a paddle wheel indirectly driven by a Savonius vertical-axis wind turbine. During the rotation of the paddle wheel, the water is heavily dispersed in atmospheric air, freed of volatile products of anaerobic decomposition and aerated. The oxygenated water is returned to the hypolimnion zone as a result of the force of gravity through the delivery hoses [25,26]. The aerators operate continuously, except when ice cover appears on the Lake. The aerators have the following characteristics: height 8 m, raft diameter 10 m, water output 200–800 m^3 a day, water aeration increase by 3–5 times [27]. One aerator was in operation at each of the lakes. Most of them were equipped with a coagulant dosing system. The exceptions were the Barlinek and Zamkowe stratified lakes, where the aerators were employed without this system.

2.3. Research Methods

The study was conducted in selected years—different for individual lakes (Table 2)—before and after installation of the aerator, during the period from 1994 to 2016. The analysis was performed at representative points (the deepest points of the lakes) and included measurements of temperature, dissolved oxygen concentration (DO) and % oxygen saturation (DO%), measured with a multi-parameter elektrochemical probe [28] throughout the range from 1 m below the water table to the bottom, with measurements being taken every 1 m. On the surface layer, the visibility of the Secchi disc (ZSD) was measured. One meter below the water table, the following concentrations were measured: chlorophyll *a* (CHL), total phosphorus (TP), and total nitrogen (TN), by means of spectrophotometry methods: CHL with acetone as extraction solvent, TP by molybdenum method after mineralization to orthophosphates in nitric and sulfuric acid, and TN calculated as sum of nitrite nitrogen, which was measured with sulphanilic acid and 1-naphtylamine; nitrate nitrogen was measured with sodium salicylate, and total nitrogen with the use of Kjeldahl method [29]. The study was conducted 2–4 times in a year during the spring (April–June) and the summer (July–September) season in accordance with the then-applicable Regulations of the Ministry for the Environment on the methods of conducting environmental monitoring.

For the purpose of assessment of trophic changes occurring in the analysed lakes, the ratio of total nitrogen to total phosphorus (TN:TP) was calculated for the results obtained in the summer season. On the basis of this ratio, the elements limiting growth of phytoplankton biomass were identified. At TN:TP below 10, nitrogen limits growth. For ratios above 17, phosphorus is the most growth-limiting nutrient. In the range 10–17, one or both of these elements limit the growth [30]. Moreover, the trophic state of the analysed lakes was determined with the use of Carlson's Trophic State Indices (TSI); TSI(TP) and TSI(CHL) were calculated based on the summer mean ZSD, TP and CHL values [31].

The differences between the annual mean TSI values for individual lakes were analysed with the use of one-way analysis of variance following the assessment of the distribution of the analysed contents against their normal distribution (Shapiro-Wilk's test) and the test for homogeneity of variances (Levene's test). The results of the tests show the lack of grounds for the exclusion of the hypothesis on normality and homogeneity of the analysed data. The significance of the differences between mean contents of the analysed elements was assessed with the use of Tukey's post-hoc test. All statistical alayses were conducted at the significance level $\alpha = 0.05$.

3. Results

In the surface water of all analysed lakes, DO% was high throughout the growing season (Table 2). In the spring season, Lake Resko Górne and Lake Zamkowe exhibited the lowest values of DO% which, on average, amounted to 85.5% and 87.3% respectively. The highest DO% was found in Lake Nowogardzkie—126.8% on average. In the summer season, mean DO% in the analysed lakes ranged from 86.0% in Lake Resko Górne to 126.1% in Lake Starzyc. In most of the analysed lakes, installation of the aerator resulted in an increase of DO% in the summer season, with the exception of the following lakes: Resko Górne, Zamkowe and Nowogardzkie, where the values of the said parameter were found to decrease.

In the summer season, the bottom waters of the stratified lakes showed no improvement in oxygen conditions; in both lakes, DO% was <0.1% (Table 2). The low DO% was also found in two unstratified lakes: Głębokie and Nowogardzkie. Oxygen profiles (Figure 1), which were identified on the basis of the results obtained before and after undertaking the remediating activities, were very similar in the individual lakes. In stratified lakes, the improving oxygen conditions were found only in the surface layer to a depth of approximately 5 m. In unstratified lakes, the increased DO in the bottom waters was found only in Lake Nowogardzkie at a depth of 7–9 m. In the remaining cases, aeration either had no effect on the oxygen profiles of the analysed lakes, or it was found that DO deteriorated after installation of the aerator.

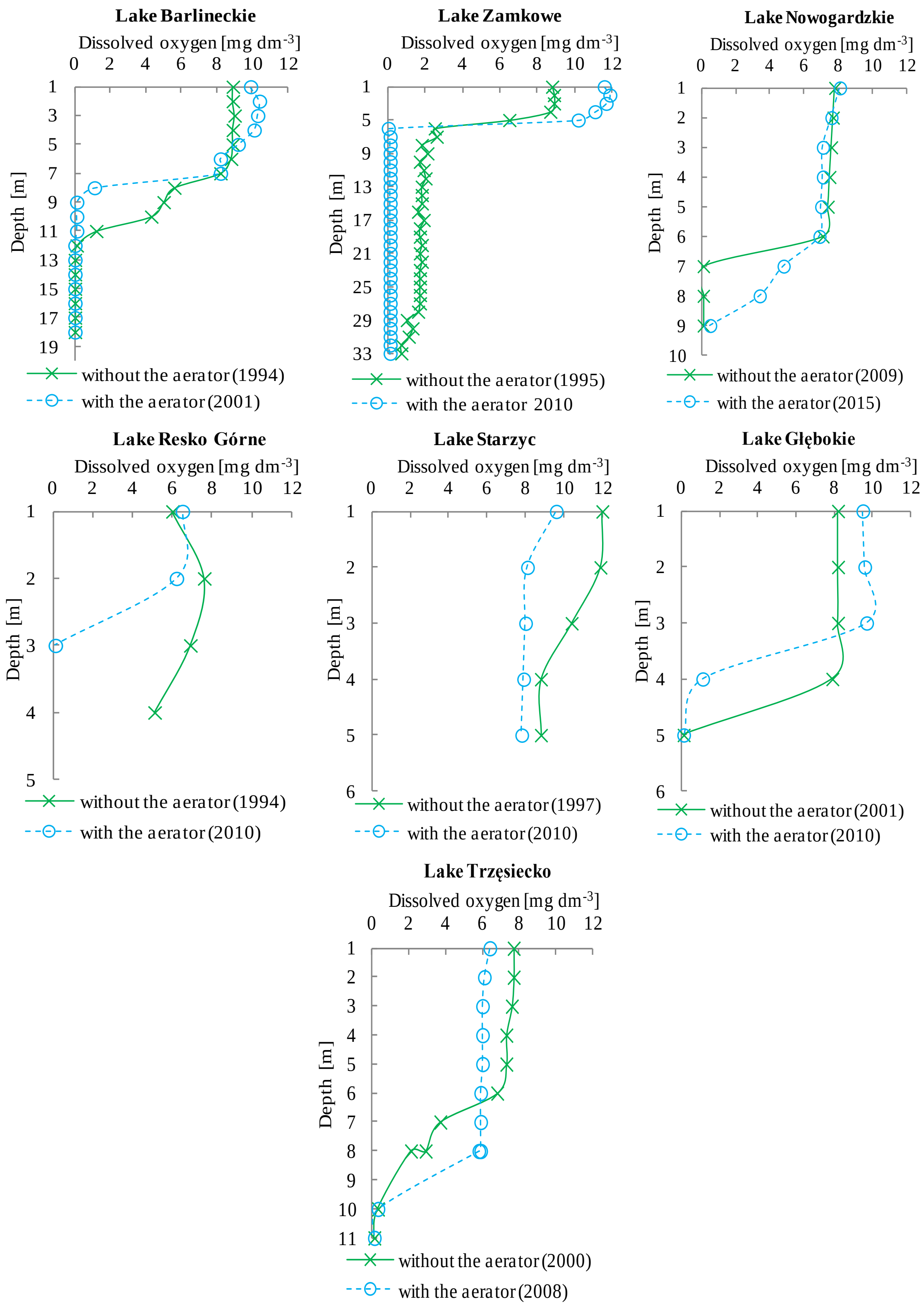

Figure 1. Example vertical profile of dissolved oxygen concentration in the water column at the deepest site of the lakes, in the summer season, before and after installation of the aerator.

In the analysed lakes, the lowest development of phytoplankton biomass was found in Lake Barlineckie; the mean CHL content calculated for all the analysed years amounted to 6.0 mg m^{-3}. The highest biomass development was found in Lake Starzyc, with a mean of 44.3 mg m^{-3}. In most of the analysed lakes, in the summer season, before deployment of the aerator, the TN:TP ratio was <10 (Table 2), which shows that nitrogen was the the most growth-limiting nutrient. The exception was lake Trzęsiecko, where the TN:TP ratio amounted to 14.1. Having installed the aerator, the TN:TP ratio was found to gradually increase in all the lakes.

The values of the indices TSI(ZSD) and TSI(CHL) ranged from 50–70 (Table 3), which classifies the analysed lakes as exhibiting a eutrophic state, whereas the values of the TSI(TP) index in most of the analysed lakes was >70, which classifies the lakes as hypertrophic. The exception was Lake Barlineckie, in which the values of TSI(ZSD) and TSI(CHL) were <50, which classifies the lake as mesotrophic. Additionally, in Lake Barlineckie, TSI(TP) values ranged from 50–70, which indicates that the lake is eutrophic in nature. The greatest improvement in the trophic state after installation of the aerator was found in Lake Resko Górne—TSI decreased on average by 21%. Testing for significance of difference between annual mean TSI values for individual lakes (Table 3) showed that in the unstratified lakes there were no significant changes in TSI after restoration activities. The exception was in Lake Resko Górne, in which there was a significant decrease in TSI(TP) and TS(ZSD). In the stratified lakes—Barlineckie and Zamkowe—there was a significant change in TSI(TP) and TS(CHL). However, in the case of Lake Barlineckie, the values of both indices decreased, whereas in the case of Lake Zamkowe only TSI(TP) showed some decrease, and the values of the TSI(CHL) index increased.

Table 3. Mean values of Carlson's Trophic State Indices: TSI(SD), TSI(TP), TSI(CHL) of the tested lakes, calculated for the individual years of the research. Different letters (a, b, c....) indicate significant differences between means TSI for the entire study period ($\alpha = 0.05$).

Lake	Aerator Installation	Year of Study	TSI(ZSD)	TSI(TP)	TSI(CHL)
Barlineckie	before	1994	35.0 ^{a}	68.5 ^{a}	46.8 ^{a}
	after	2001	34.8 ^{a}	60.5 ^{b}	31.5 ^{b}
		2010	41.8 ^{a}	56.3 ^{cb}	38.2 ^{c}
		2016	39.9 ^{a}	53.1 ^{dc}	45.0 ^{ca}
Zamkowe	before	1995	50.6 ^{a}	92.3 ^{a}	43.1 ^{a}
	after	2010	59.9 ^{a}	72.5 ^{b}	71.4 ^{b}
		2015	53.7 ^{a}	78.1 ^{c}	63.6 ^{c}
Resko Górne	before	1994	61.5 ^{a}	99.7 ^{a}	75.0 ^{a}
	after	2010	77.3 ^{b}	71.5 ^{b}	64.0 ^{a}
		2015	59.4 ^{a}	76.2 ^{c}	62.1 ^{a}
Starzyc	before	1997	60.9 ^{a}	86.9 ^{a}	70.5 ^{a}
	after	2010	65.7 ^{ab}	76.3 ^{a}	66.1 ^{a}
		2016	72.4 ^{bc}	78.9 ^{a}	72.9 ^{a}
Trzęsiecko	before	2000	51.0 ^{a}	73.7 ^{a}	55.2 ^{a}
	after	2008	51.8 ^{a}	66.8 ^{ab}	53.2 ^{a}
		2010	58.1 ^{b}	65.2 ^{bc}	61.4 ^{a}
		2011	54.7 ^{ab}	66.3 ^{ca}	56.4 ^{a}
		2016	54.7 ^{ab}	65.4 ^{ca}	58.6 ^{a}
Głębokie	before	2001	56.8 ^{a}	58.9 ^{a}	52.8 ^{a}
	after	2010	55.5 ^{a}	67.2 ^{b}	61.1 ^{a}
Nowogardzkie	before	1997	93.1 ^{a}	93.1 ^{a}	65.3 ^{ad}
		2005	60.0 ^{a}	84.8 ^{a}	70.1 ^{ba}
		2009	50.9 ^{b}	80.8 ^{a}	53.6 ^{c}
	after	2015	51.1 ^{b}	74.3 ^{a}	57.6 ^{dc}

Comparison of the particular indices values shows that TSI(TP) > TSI(CHL) = TSI(SD) for most of the analysed lakes (Table 4). The exceptions were lakes Resko Górne and Głębokie, where no significant differences between the values of these indices were found.

Table 4. Mean values of Carlson's Trophic State Indices: TSI(SD), TSI(TP), TSI(CHL) of the tested lakes calculated for the entire study period. Different letters (a, b) indicate significant differences between the mean TSIs calculated for the individual lake (α = 0.05).

Lake	TSI(CHL)	TSI(ZSD)	TSI(TP)
Barlineckie	41.7 ± 6.7^{a}	38.6 ± 3.4^{a}	58.7 ± 6.1^{b}
Zamkowe	59.4 ± 9.5^{a}	54.7 ± 4.7^{a}	81.0 ± 9.2^{b}
Resko Górne	67.0 ± 6.9^{a}	66.1 ± 9.8^{a}	82.5 ± 9.1^{a}
Starzyc	70.1 ± 2.8^{a}	67.2 ± 5.0^{a}	80.8 ± 4.1^{b}
Trzęsiecko	56.9 ± 3.1^{a}	54.0 ± 2.8^{a}	67.5 ± 3.5^{b}
Głębokie	56.7 ± 4.2^{a}	57.3 ± 2.0^{a}	62.9 ± 4.1^{a}
Nowogardzkie	61.7 ± 7.4^{a}	55.1 ± 4.7^{a}	83.3 ± 7.8^{b}

4. Discussion

Multiannual study of seven eutrophic lakes that underwent restoration by means of pulverising aeration did not show changes in oxygen conditions of the bottom waters in either stratified or unstratified lakes. The two stratified lakes, as well as two of the unstratified lakes under analysis, showed mean DO in the bottom waters < 1 mg dm^{-3} in summer throughout the study period. This indicates hypoxia, with a threshold concentration value of dissolved oxygen 2 mg dm^{-3} [32]. The oxygen profiles presented in this paper show that oxygen conditions were improved in the surface layers of the three lakes, and that in the two unstratified lakes, the conditions deteriorated throughout the profile. Only a few authors have unequivocally confirmed the efficiency of aeration of the bottom waters [14,19,26,33], e.g., by means of side stream saturation [24]. The high efficiency of this method was confirmed in a shallow drinking water reservoir (maximal depth = 9.3 m) where concentration of dissolved oxygen was found to increase. Most authors conducting research on the effects of hypolimnion aeration found no sustainable improvement in oxygen conditions in the analysed lakes. Hypolimnion oxygenation conducted in five stratified lakes in Denmark over a period of 4 to 20 years resulted in a significant increase in hypolimnetic oxygen level in only one lake—the remaining four lakes still exhibited low mean levels in summer (<2.2 mgO_2 dm^{-3}) [21].

Pulverising aeration of waters is a method of lake restoration very often used in Poland. Even early studies showed the device should be equipped with an autonomous system designed to inactivate phosphorus [34]; therefore, chemical inactivation of phosphorus and biomanipulation have typically accompanied this activity. Monitoring tests of aerated water of the chosen lakes—Panieńskie, Trzęsiecko, Uzarzewskie and Swarzęckie—showed an improvement of water quality—reduction of CHL content, reduction of phosphorus budget available for phytoplankton in the vegetation period, and an increase of water transparency [26,35–37]. Authors of the cited papers found no improvement of DO of the hypolimnion zone; the exception was Lake Panieńskie, where improvement of DO was recorded [26]. The research by Wesołowski and Brysiewicz [38] carried out in Lake Starzyce showed that concentrations of ammonium-nitrogen, nitrate nitrogen and DO in water near the aerator did not differ from those in sites 200 m and 150 m away, which indicated similar abiotic conditions in the studied waters. As a result, bottom sediments remained an internal source of phosphate for the lake [39]. Similar results were obtained in Lake Swarzędz, in which, one year after the aerator was installed, there was no significant effect on the oxygenation of the hypolimnion zone, which could have resulted from the extremely large oxygen demand of the bottom sediments [37]. Therefore, when using pulverising aeration, attempts are typically made to undertake other restoration activities aimed at increasing the redox potential in the hypolimnion zone, e.g., by supplying this zone with cold ground water abundant in nitrates, transported from the springs with pipelines [36].

Having installed the aerator, in all the lakes under study, the recorded successive increase of the TN:TP ratio indicates that aeration may decrease phosphate in the water column by precipitation resorption. In three lakes—Barlineckie, Głębokie and Trzęsiecko—the ratio was >17, so there was a change of the element limiting the growth of phytoplankton from nitrogen to phosphorus.

Hence, the pulverising aeration of waters may shift the balance of phosphorus circulation at the water/sediment interphase towards deposition of phosphorus in the sediment. It should be noted that such changes may be connected with other protective measures taken as a part of the main remediating process—pulverising aeration. The first of these could be the reduction of allochthonous phosphorus sources. The implementation of the Water Framework Directive has caused changes in water and wastewater management in Poland. The total amount of the treated sewage increased by about 37.9% in the multi-year period between 1980 and 2007, whereas the amount of untreated sewage delivered to the environment decreased by as much as 83.4%. The direct symptom of improvement in the situation was the decrease by about 59% of general phosphorus in the sewage drained into water in the multi-year period between 1995 and 2006 [40]. A second protective measure could be the chemical removal of phosphorus from the water column by means of coagulants [10–12]. The research of the bottom sediments of Lake Nowogardzkie conducted in the summer seasons of 2012–2014 showed significant reduction of P concentration in interstitial water—from 6.5 mgP dm^{-3} in 2012 to 3.3 mgP dm^{-3} in 2014. Internal P loading was at its highest in 2012, reaching over 24 mg P m^{-2} d^{-1}. After restoration treatment, up to 2 mg P m^{-2} d^{-1} accumulation in sediments was noted [41]. Even the single Fe application still ensures the high P binding ability of the sediment, since Fe relocates towards the surface. Application of Fe, particularly when external P loading has been reduced beforehand, is a suitable lake restoration tool for stabilising a new long-lasting equilibrium in lakes [42].

In the tree lakes under study—one stratified and five unstratified, there was a change of the element limiting the growth of phytoplankton from nitrogen to phosphorus. Limitations to algae development in the analysed lakes due to phosphorus were not confirmed by the analysis of particular values of TSI indices, the formulas of which are interrelated by linear regression models and should produce the same TSI value for a given combination of variable values. In cases where there is no such correspondence, the relationship between the partial indices (TSI(TP), TSI(CHL), TSI(SD) can be applied for the purpose of identification of prevailing conditions in the water reservoir limiting phytoplankton biomass [43,44]. The values of TSI calculated for the analysed lakes were either comparable, o r the value of TSI(TP) was higher than one or two of the remaining indices. Such results indicate that in the analysed lakes, the development of phytoplankton biomass is limited by some factor other than phosphorus, e.g., zooplankton grazing, nitrogen, or the adverse effects of toxins. In the case of the lakes under analysis, this could very well stem from the remediation activities taken—aeration and coagulation. The restoration activities had no significant effect on the Carlson trophic state indices (TSI) in the study period, but only for the unstratified lakes; in the stratified lakes—Barlineckie and Zamkowe—there was a significant decrease of TSI(TP).

The fact that hypolimnion aeration does not always affect the trophic state of a lake has been confirmed by many authors [20,21,33,39,45,46] This was additionally confirmed by the experiment conducted in Lake Jyväsjärvi, where hypolimnion aeration was ceased, and which, in turn, had an extremely negative impact on the oxygen conditions in the hypolimnion, but showed no significant effect on the trophic state of the lake [20]. The results of multiannual studies on the efficiency of lake aeration seem to call into question the paradigm that oxygen controls the release of phosphorus from sediments [47,48]. Anaerobic sediments generally do not affect the productivity of lakes, and phosphorus is permanently deposited only in the deeper layers of the sediment [49]. Many notable authors have claimed that both the release of phosphorus and oxygen depletion result from the increased trophic state of a reservoir. Long-term study of phosphorus mobilisation from the bottom sediments indicates a vast array of mechanisms of phosphorus release from bottom sediments that are not controlled by redox conditions. One such mechanism is the enzymatic regeneration of orthophosphates, or the adsorption and chemical bonding of phosphorus with compounds of aluminium and calcium, which are controlled by a change in pH [48]. The results of the efficiency analysis of pulverising aeration of the seven lakes increase the concern for finding effective restoration methods for eutrophicated water bodies. Aeration helps alleviate some symptoms of eutrophication, but it does not contribute to solving the problem, especially in the case of unstratified lakes.

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